# Advanced Emission Controls for Natural Gas Vehicles

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**DOE Natural Gas Vehicle Technology Forum**

Manufacturers of Emission Controls Association

(www.meca.org)

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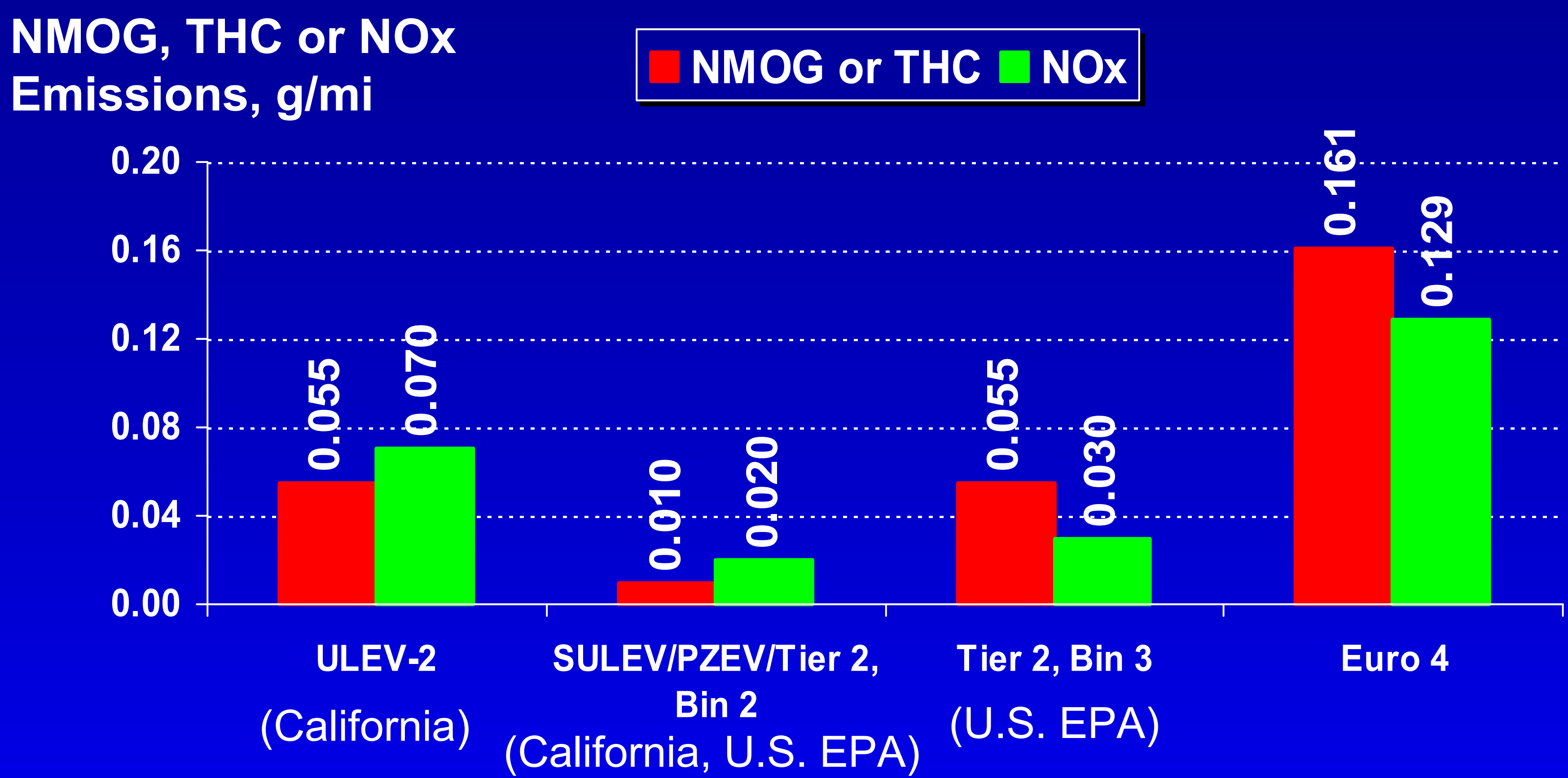
# Outline

- Stoichiometric Engines
  - Light, Medium, and Heavy-Duty NG Vehicles
- Lean Burn Heavy-Duty NG Engines
- Conclusions

# Future Emission Standards Continue March to Near-Zero Emission Categories for Light-Duty Vehicles




> Ultra-low Gasoline Sulfur Levels Facilitate Near-Zero Emission Targets: CA: 15 ppm S max; U.S.: 30 ppm S max; EU: moving toward 10 ppm S max.

# First SULEVs/PZEVs Introduced in 2001 with More to Come

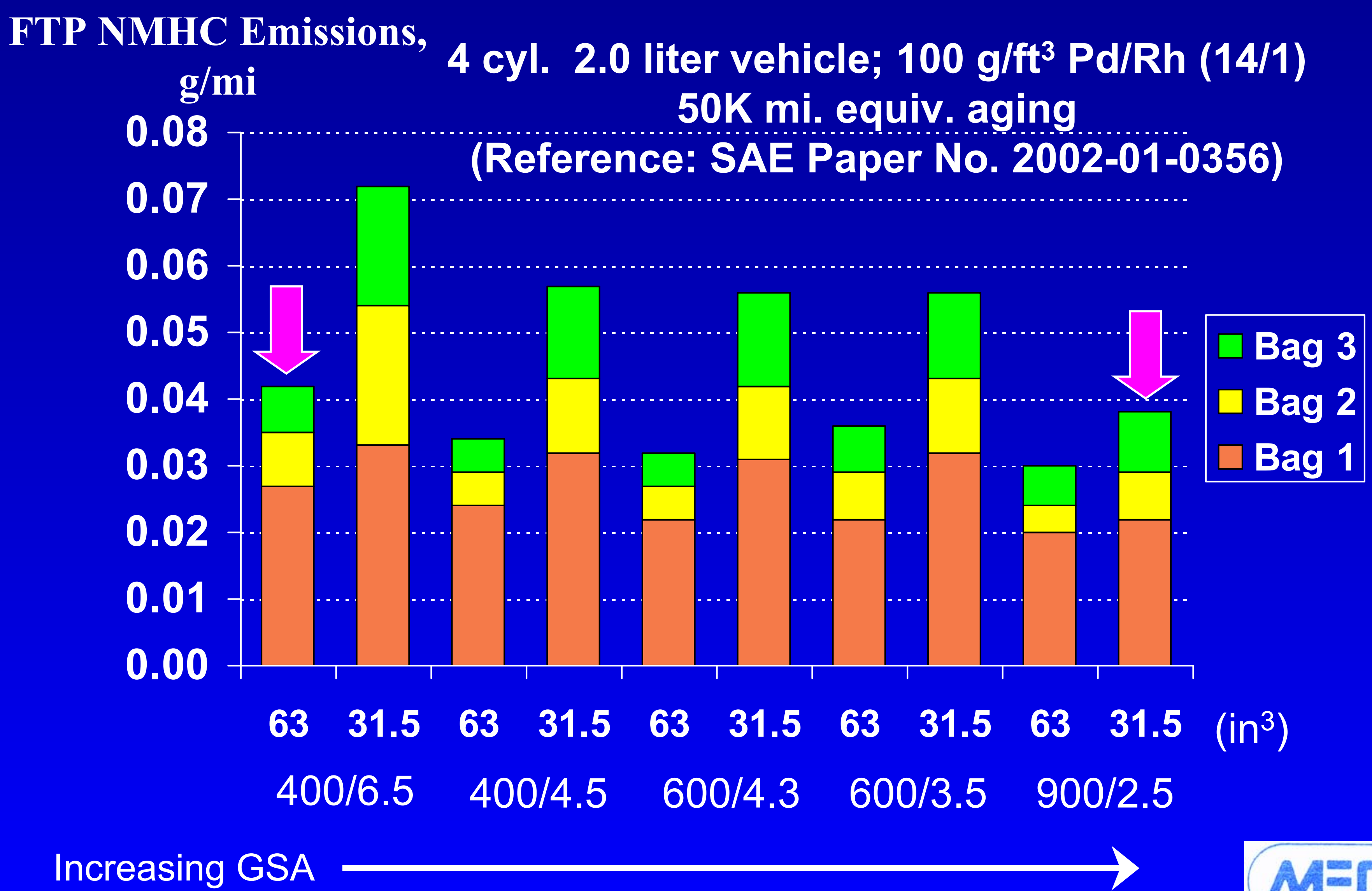
- SULEVs sold in California
  - Honda Accord SULEV (2.3 liter I4)
  - Toyota Prius SULEV (1.5 liter I4, 33 kW electric drive)
  - Nissan Sentra-CA SULEV (1.8 liter I4)
    - first PZEV (meets zero evap. requirements and is certified for 150K mile durability)
  - **Honda CNG Civic SULEV**
  - Seven different OEMs offer gasoline PZEVs for MY 2003
    - BMW, VW, Volvo, Ford, Nissan, Honda, Toyota
    - 4, 5, & 6 cylinder engine

# Near-Zero Emission Systems Include Advanced Engine Designs and Emission Controls

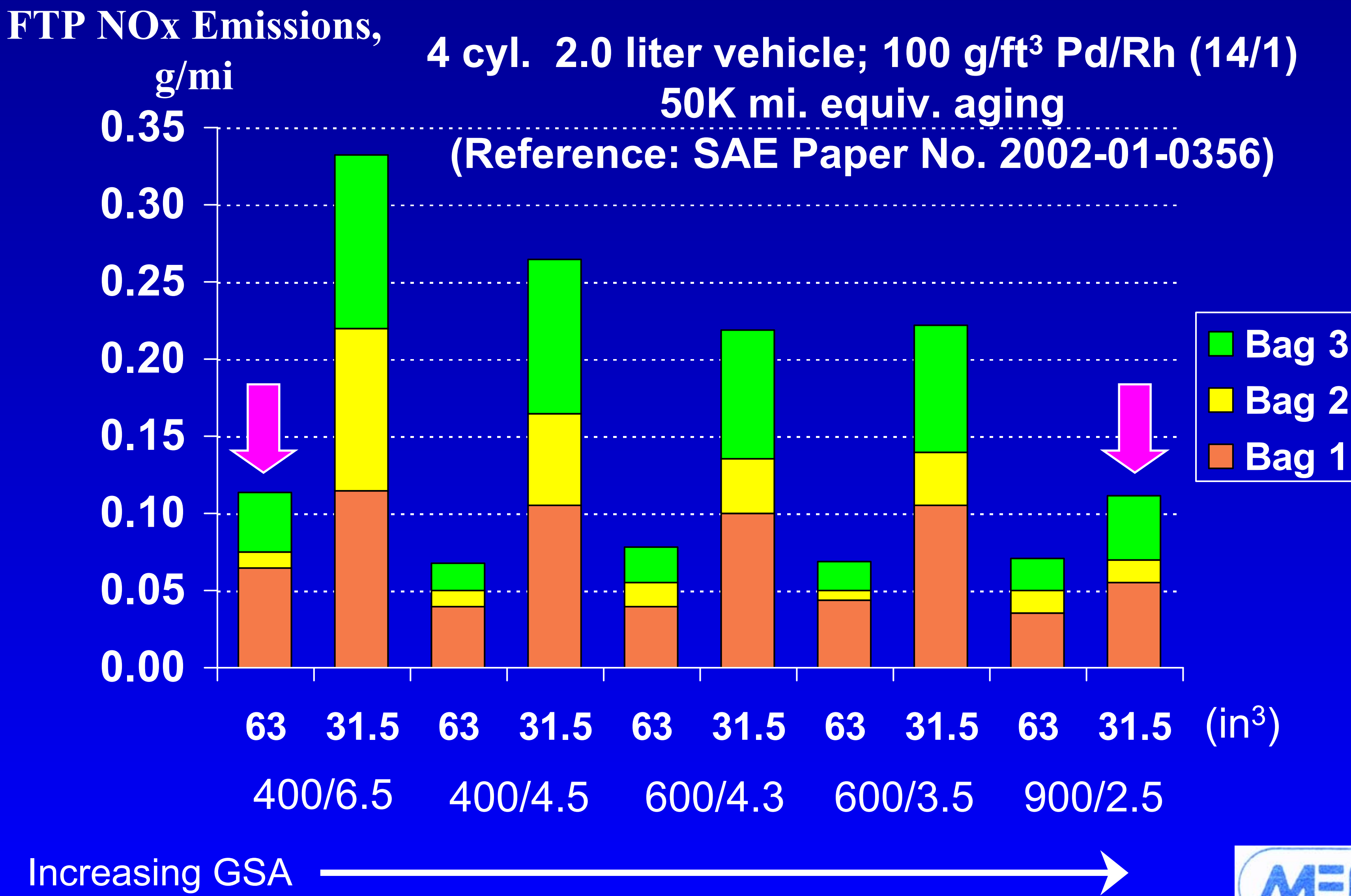
- Advanced Emission Control Technologies include:
  - Advanced thermally stable, oxygen storage materials
  - In many cases, layered TWC coating architectures
  - In some cases, HC adsorber functions
  - High cell density substrates
  - Fast response oxygen sensors
  - Secondary air systems
  - Thermal management hardware including air-gap pipes & low heat capacity manifolds

- Advanced Engine Technologies include:
  - Improved fuel injectors
  - Variable valve technology
  - Lean start strategy with spark retard for fast catalyst heat-up
  - Electrically controlled EGR valve
  - Advanced control algorithms for precise A/F control

# Advanced Substrates Provide Significant Impacts on HC Emissions and PGM Usage



## Similar Advantages on NOx Emissions with Advanced Substrates



# Advanced Stoichiometric Emission Control Technologies are Also Effective on Medium-Duty CNG Engines (6.0 Liter V8)

| Test Description | THC g/bhp-hr | CH4 g/bhp-hr | NMHC g/bhp-hr | CO g/bhp-hr | NOx g/bhp-hr | NOx+NMHC g/bhp-hr |
|---|---|---|---|---|---|---|
| Production Converters 125 hrs CNG hot runs average | 0.36 | 0.345 | 0.015 | 1.04 | 0.202 | 0.217 |
| Advanced Catalysts 125 hrs CNG hot runs average | 0.101 | 0.095 | 0.006 | 0.931 | 0.08 | 0.086 |
| Emissions Reductions | **72%** | **72%** | **60%** | **11%** | **61%** | **61%** |

- Substantial reductions in NOx, THC, and methane emissions with baseline gasoline TWC precious metal loadings and high cell density substrates

Source: NREL/SCAQMD Next Generation NG Vehicle Test Program

# Stoichiometric NG Heavy-Duty Engines: European Transit Buses

- Total of 8 in operation in Helsinki with TWCs; DaimlerChrylser stoichiometric engine design


- Stoichiometric engines also offered by Iveco and MAN; operating in Brussels transit fleet along with DaimlerChrysler stoich. engines

# Helsinki Experience

Stoichiometric CNG Buses

- Reliability, Performance, and Maintenance Have Been Good
- Equipped with TWC technology to reduce HC, CO, and NOx emissions
- Fuel Consumption on Energy Basis 15-20% Over Diesel

# Advanced Natural Gas Engine Utilized Cooled EGR, Turbocharging, and 3-Way Catalytic Converter (ETH-Zurich)

| NOx | | CO | | THC | | BMEP | Engine Efficiency | Operating Mode |
|---|---|---|---|---|---|---|---|---|
| $mg/m_N^3$ ($5\%O_2$) | g/kWh | $mg/m_N^3$ ($5\%O_2$) | g/kWh | $mg/m_N^3$ ($5\%O_2$) | g/kWh | Bar | % | |
| ~1 | ~0.003 | $\leq$75 | $\leq$0.21 | $\leq$30 | $\leq$0.08 | 12/20 | ~40/42 | EGR, $\lambda$=1 and 3-Way Catalyst |
| <250 | <0.79 | <650 | <2.05 | ~1000 | ~3.15 | 12 | ~36.5 | EGR, $\lambda$>1 Without Catalyst |
| 250 | 0.76 | 100 | 0.30 | 1500 | 4.54 | 12 | 38 | $\lambda$>1 With Oxidation Catalyst |

**Source: SAE Technical Paper – 2000-01-2825**

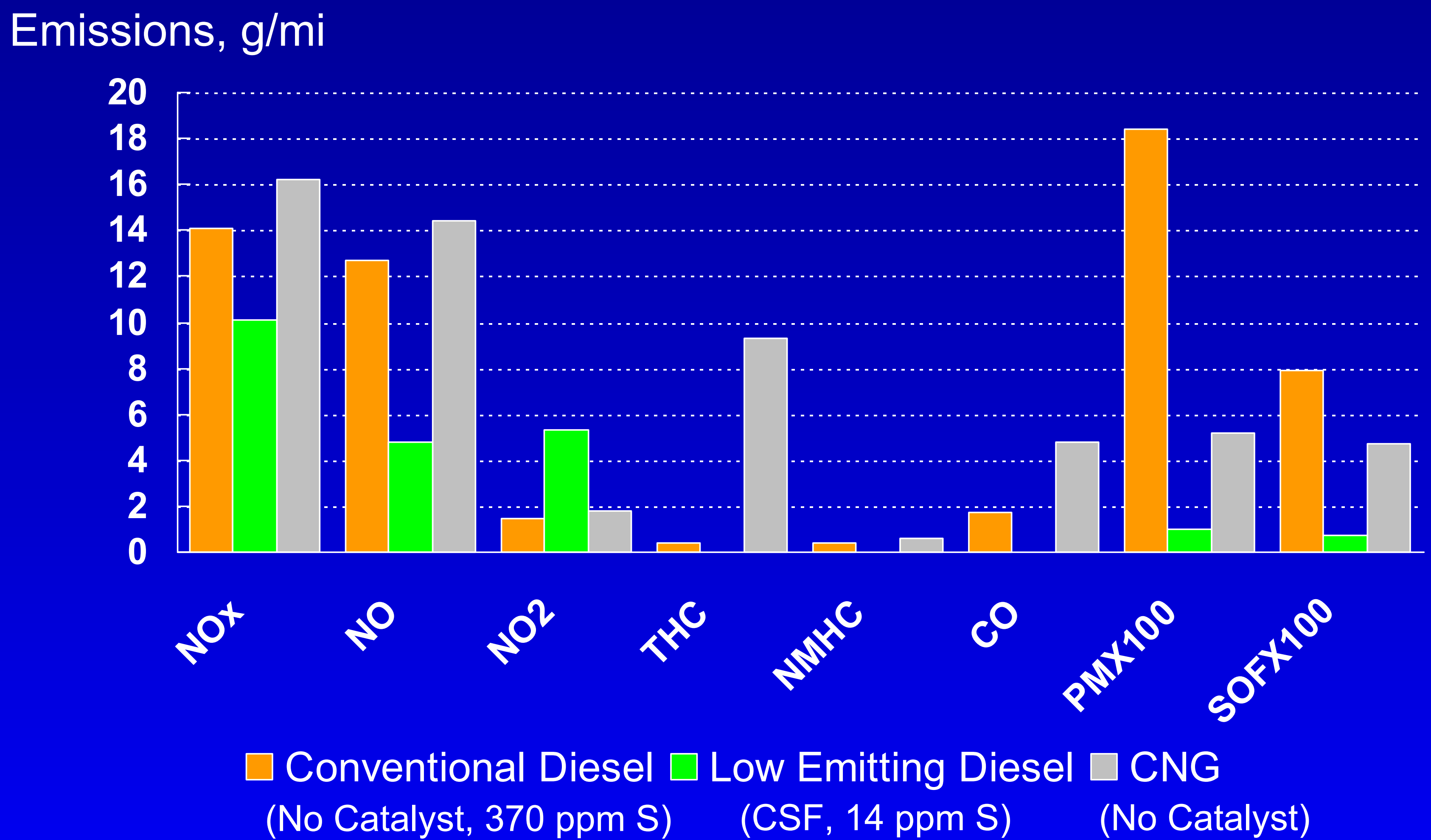
***Outstanding Emissions Control and Engine Efficiency Through Engineering:***

1) ***Reduced Cylinder Temperatures and Knock Limits Through Use of Cooled EGR***
2) ***Achieved Engine Efficiency Through Maximum Use of Turbocharging***
3) ***Emissions Control with Stoichiometric Calibration and the Proven 3-Way Catalytic Converter***

# Lean Burn Heavy-Duty NG Engines Are Dominant in the U.S.

- Lean-Burn Engines
  - Potential best fuel economy
  - Easiest NG engine modification (using diesel engine technology base)
  - HC, CO, and toxic HC emissions can be effectively reduced with catalyst-based technologies
  - PM emissions can be effectively reduced with catalyzed filter technologies
  - NOx emission reductions available with EGR systems and lean NOx catalytic strategies

# School Bus Emissions Comparison: City-Suburban Heavy Vehicle Drive Cycle




**Source: International/Conoco October 2002 Study**

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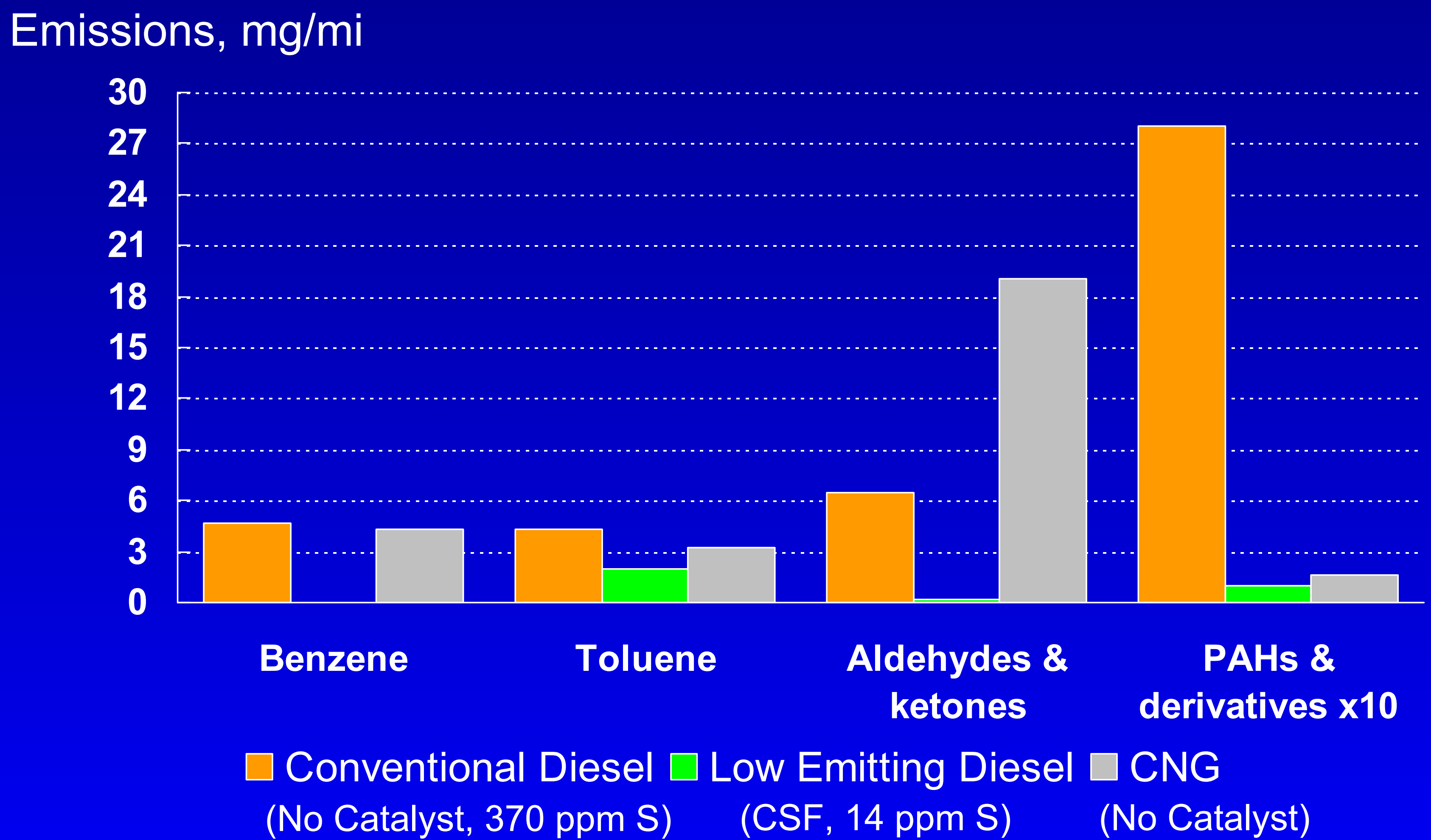


Source: International/Conoco October 2002 Study

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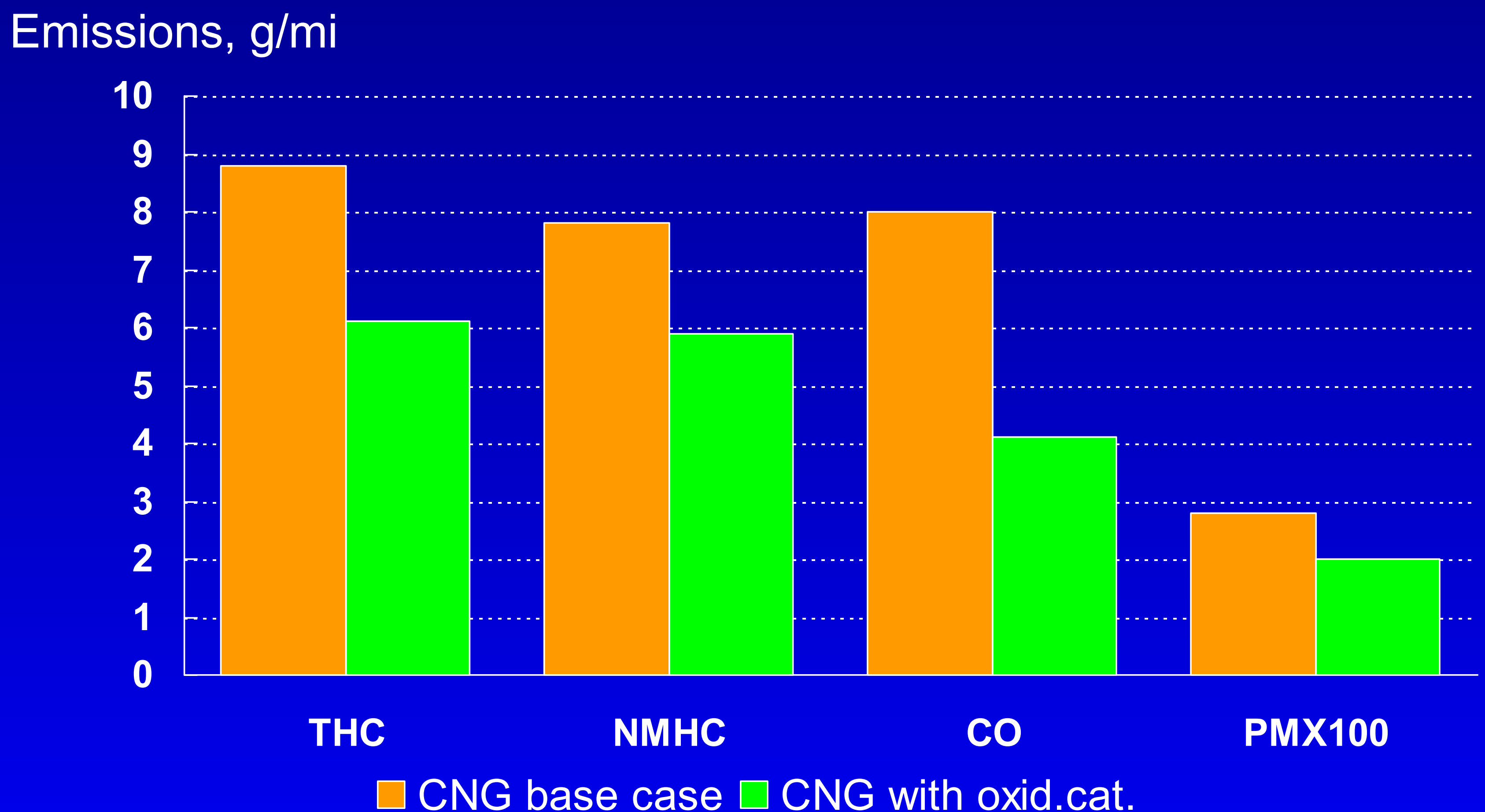
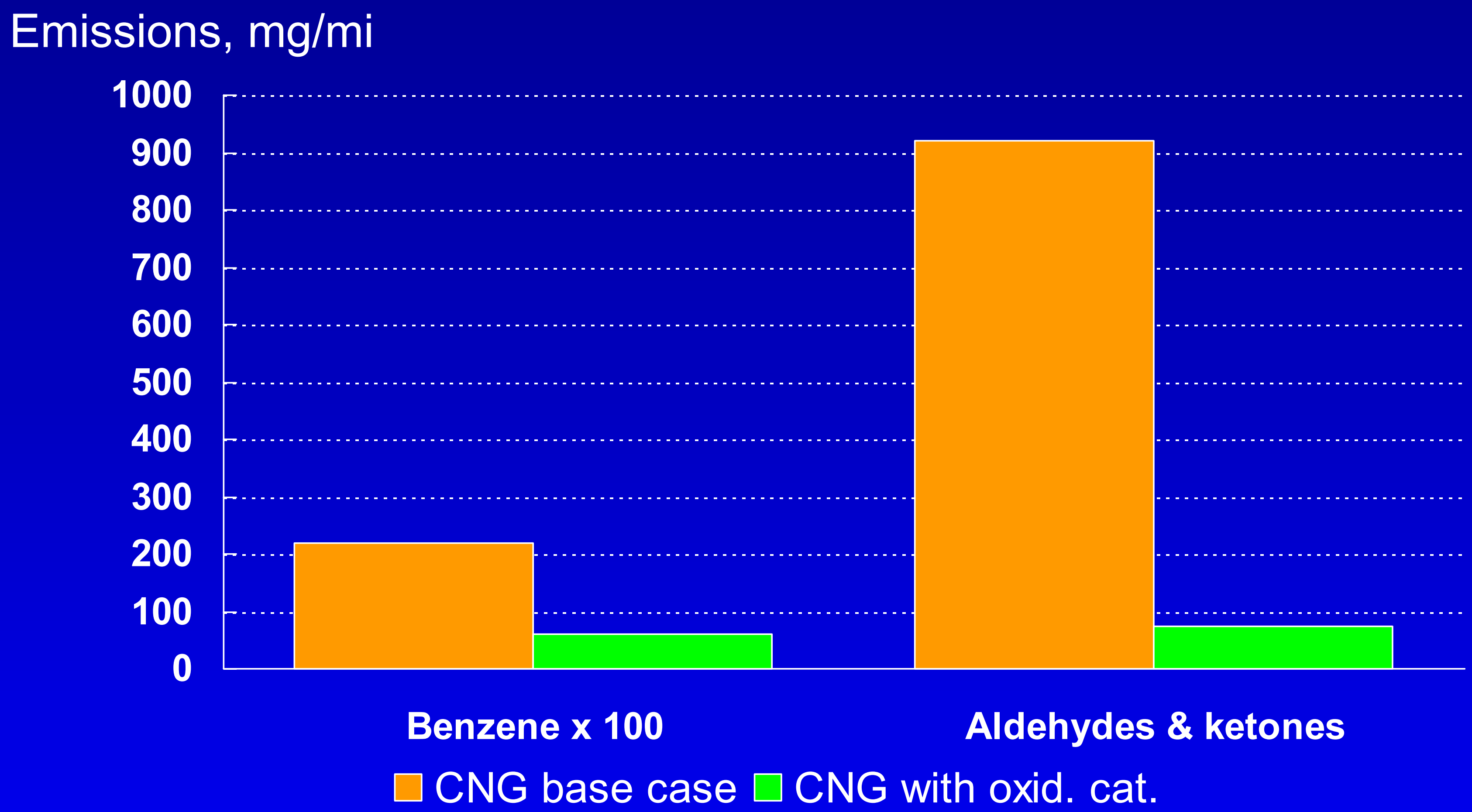
# ARB Transit Bus Emissions Comparison: City Business District Drive Cycle




L.A. MTA Bus with Series 50G DDC Engine (56,600 miles for base case results)

Source: ARB presentation at August 2002 DEER Conf.

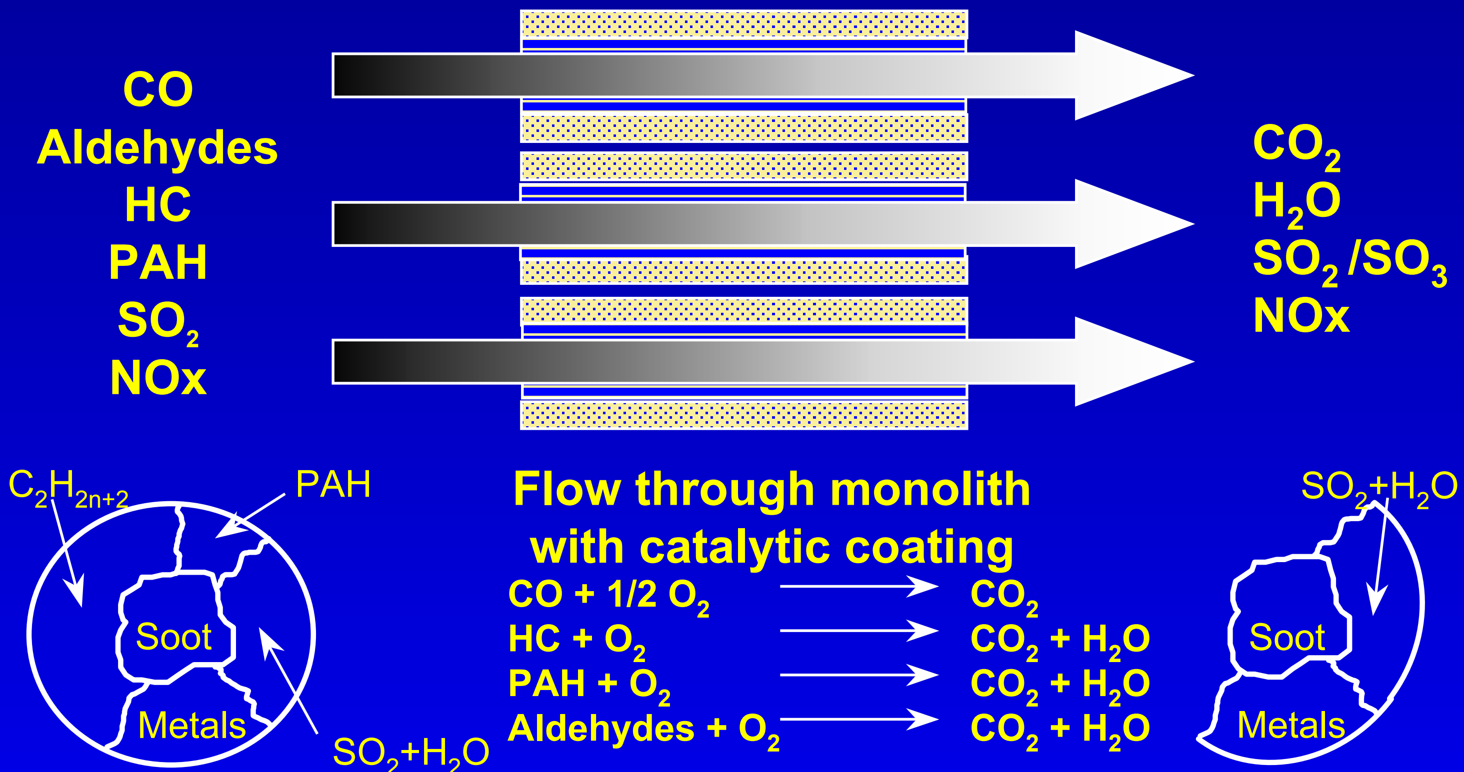
# Oxidation Catalyst Significantly Reduces Toxic HC Emissions on CNG Transit Bus




City Business District Drive Cycle Results; Oxidation Catalyst with 4K miles

**Source: ARB Presentation at August 2002 DEER Conf.**

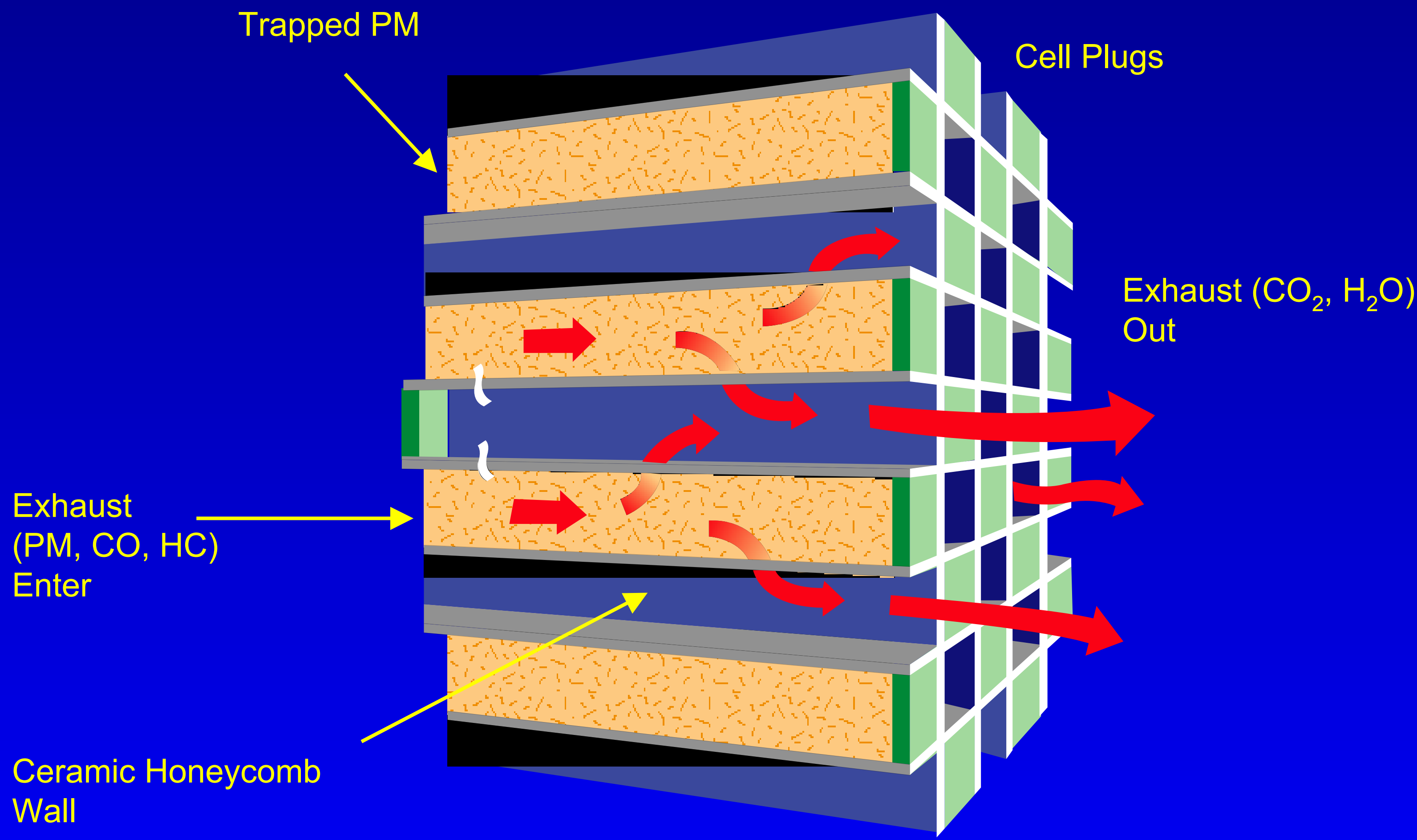
# Oxidation Catalyst



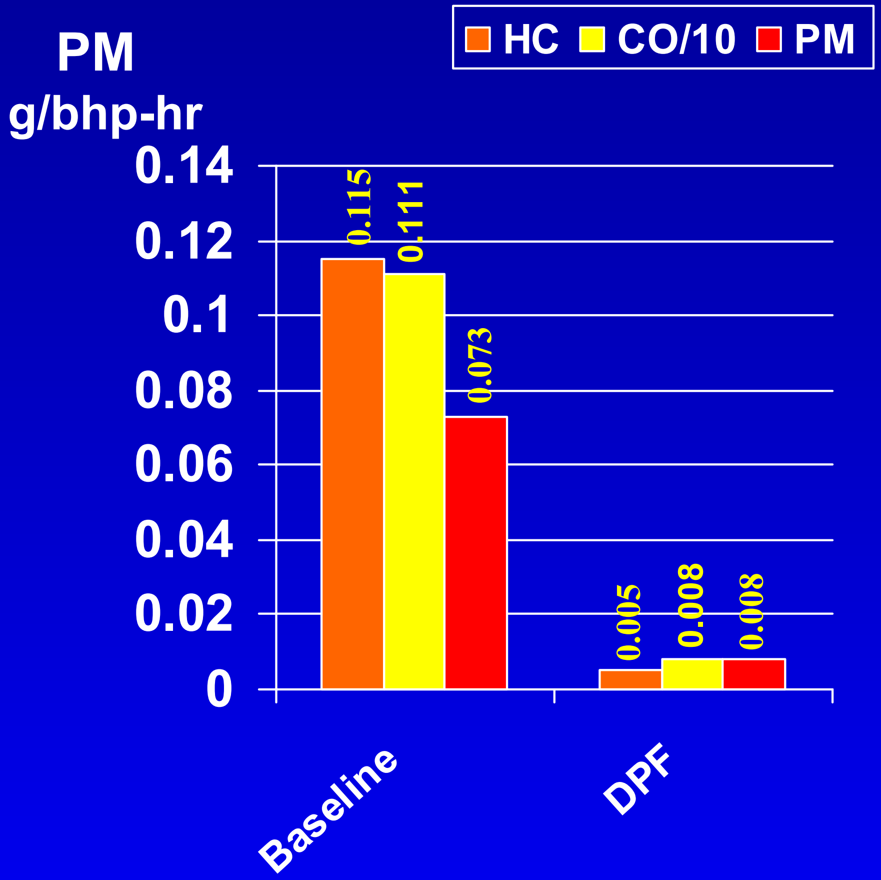
# Oxidation Catalysts Are Efficient and Have Excellent Operating Experience

- Oxidation Catalyst Control Capabilities
  - PM – 20-50% Reduction
  - CO and HC – up to 90% Reduction
  - Toxic HCs – up to 70% Reduction
- Oxidation Catalyst Operating Experience
  - >250,000 Off-Road Engines
  - > 60,000 Urban Buses in the U.S., Europe, & Asia
  - Hong Kong initiating program with > 40,000 retrofits
  - >1,500,000 Class 1 & 2 Vehicles (Pick-Ups)
  - >35,000,000 LDD vehicles in Europe

# Particulate Filters



# Particulate Filters Nearly Eliminate PM




- PM Emissions Below 0.01 g/bhp-hr Can Be Achieved
- Significant Reductions in CO and HC Emissions Can Also Be Achieved
- Several Design Options Available:
  - Catalyzed Filter
  - Cont. Regenerative Design (DOC+Filter)
  - Filter + Fuel-Born Catalyst (PSA system)

Source: MECA 1999

# Particulate Filters Are Efficient and Are Developing an Impressive Track Record

- Filter Control Capabilities
  - PM – >85% Reduction with ULSF
    - Carbon-based Ultra-fine Particulate - > 99% Reduction
  - CO and HC – up to 90% Reduction
  - Toxic HCs – up to 90% Reduction
- Filter Operating Experience
  - > 400,000 OE systems operating in Europe on passenger cars
  - U.S. & European OE certified systems for HDD
  - Over 50,000 Systems Have Been Retrofitted to Onroad HDD Vehicles Worldwide
  - Over 20,000 Non-Road Engines Equipped (Both OE Installed and Retrofit), Including Both Passive and Active Systems
  - Three Level 3 (> 85% PM reduction) Filter Systems Verified in CA for Retrofit including one for CNG/Diesel Bi-Fuel Applications

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# NOx Reduction Technologies

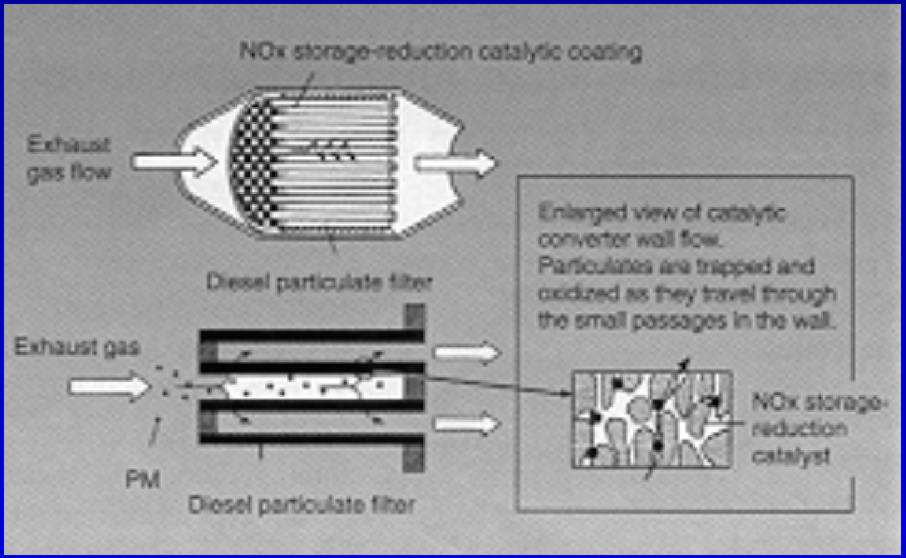
- Technology development includes:
  - NOx Adsorbers
    - High sulfur sensitivity; durability studies for heavy-duty applications underway
  - Selective Catalytic Reduction
    - Infrastructure for on-board reductant (e.g., urea)

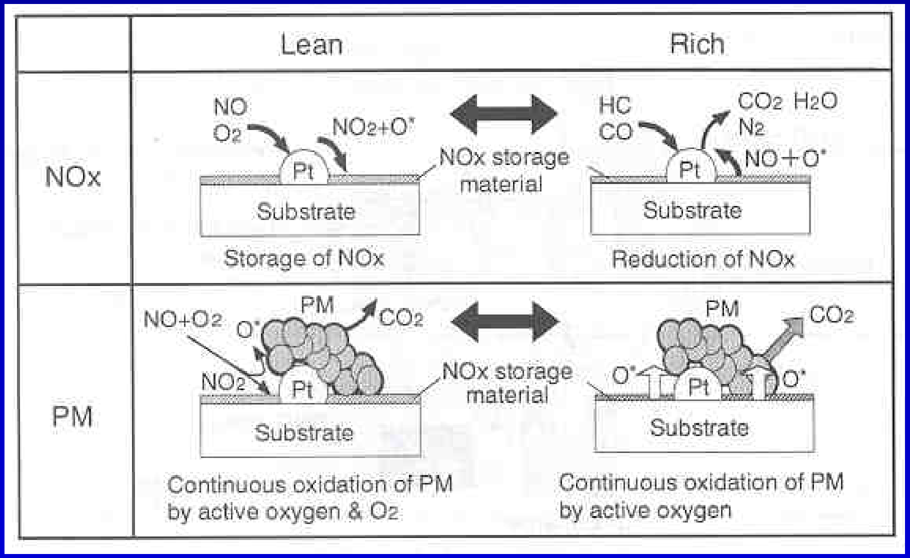
# Progress in Developing NOx Adsorber Technology

- NOx Adsorber Technology Has Demonstrated the Capability of Control Up to 90% or More Under Certain Operating Conditions
- Light-duty operating experience in Europe and Japan with Partial Lean GDI Engines
- Focus of Current Development Efforts
  - Improvements to broaden the temperature range over which the NOx adsorber is effective (temperature window)
  - Improvements in thermal durability (resistance to thermal sintering)
  - Improvements in methods and performance for desulfation (sulfur cleansing)
  - Improvement in systems integration (NOx regeneration, packaging, fuel economy)
- Little experience with NG; Methane likely a poor choice for reductant

# Catalyst Integration for NOx Adsorbers and Filters Is Being Developed

## Toyota DPNR System




- NOx trap material is coated directly on wall-flow filter (> 80% NOx + PM reductions)
- "Active oxygen" aids filter regeneration
- Achieved Tier 2, Bin 5 NOx and PM levels in U.S. EPA tests
- 60 vehicle test fleet underway in Europe

Aachen Symposium 10/02 and SAE paper no. 2002-01-2877

# SCR Has Been Used Successfully on Stationary Sources and Is Now Used for Mobile Sources

- SCR Control Capabilities (w/ Integral Oxidation System)
  - PM – 20-50% Reduction
  - CO and HC – up to 90%
  - Toxic HCs – up to 70%
  - NOx – 50 to 90%
- SCR Operating Experience
  - Extensive Operating Experience with Gas Turbine Power Generation Applications
  - HD Truck Demonstration in Europe since 1995 with Mileage Exceeding 200,000 miles
  - Several U.S. Demonstrations Currently in Process for HDD On-Road

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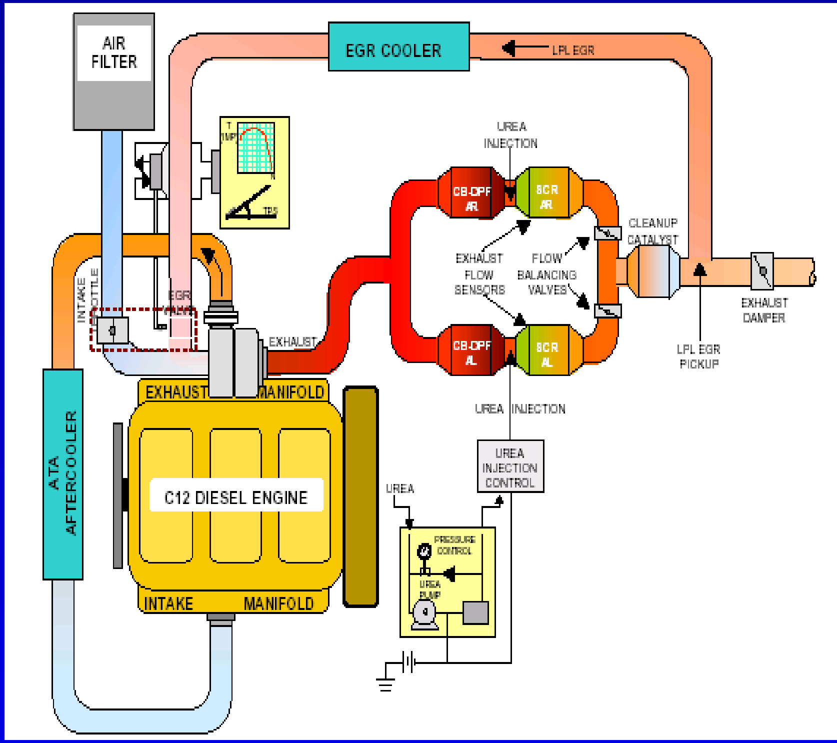
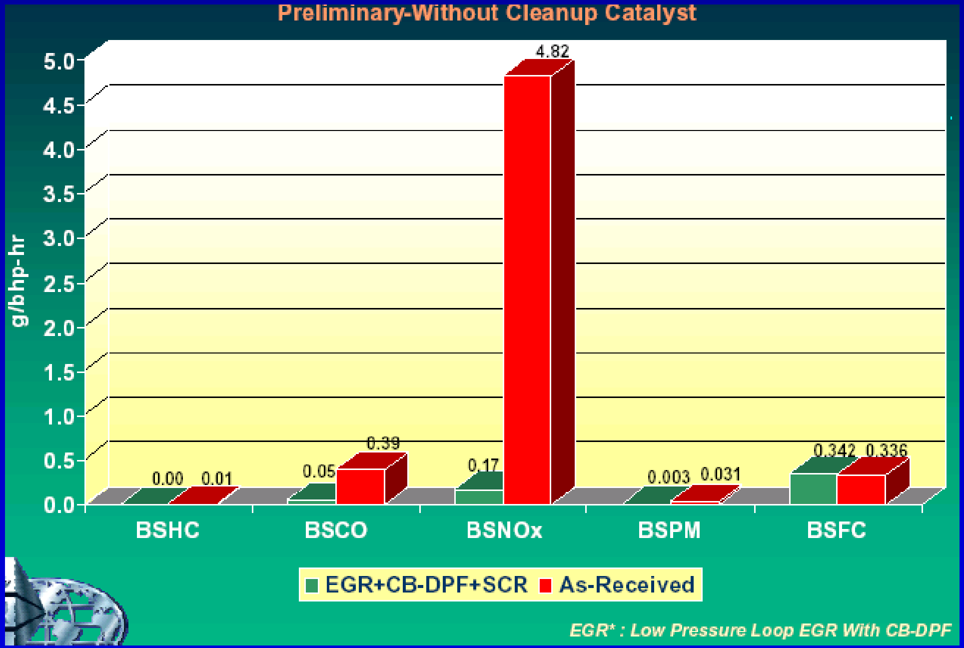
# A C-12 engine achieved US 2010 PM/NOx levels with DPF/SCR in steady-state testing




SwRI APBF DEER 8/02

# Short Term Solutions

- Oxidation catalysts can be applied today to both new and existing NG engines to achieve substantial reductions in toxic HC emissions
  - Many NG HDVs are operating in the U.S. without oxidation catalysts
- Demonstrations underway to show benefits of PM filter technology in reducing PM from NG engines (SCAQMD & NREL funding)

# Long Term Solutions

- California and Federal 2007 On-Road HDE Standards will provide the regulatory incentive for engineering and commercializing the NG HDE of the future, including:
  - Stoichiometric NG Engine with Three-Way Catalyst Technology
  - Lean-Burn NG Engine with Oxidation Catalyst and NOx Exhaust Controls
  - PM Filters for NG Engines

# Conclusions

- NG engines can take advantage of proven emission control technology today
- 2007 HDE rule will change the NG engine system significantly; systems engineering required
- Regulations/Standards, Policies, Incentives, and Demonstration Programs all can play a role in ensuring that NG engines are as low emitting as possible